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Low-Power, Low-Voltage Resistance-to-Digital Converter for Sensing Applications

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Abstract: IC (ASIP) of Universal Sensors and Transducers Interface (USTI-MOB) with low power consumption, working in the resistive measurement mode (one of 26 possible measuring modes) is described in the article. The proposed IC has 20 … 4 500 000 Ω range of measurement, relative error < ±0.04 %, 0.85 mA supply current and 1.2 V supply voltage. The worst-case error of about < ±1.54 % is observed. IC has three popular serial interfaces: I2C, SPI and RS232/USB. Due to high metrological performance and technical characteristics the USTI-MOB is well suitable for such application as: sensor systems for IoT, wearable and mobile devices, and digital multimeters. The ICs can also work with any quasi-digital resistive converters, in which the resistance is converted to frequency, period, duty-cycle or pulse width. *Copyright © 2016 IFSA Publishing, S. L.*

Keywords: Resistance-to-digital converter, USTI-MOB, Resistance-to-frequency converter, Resistive sensors, Resistive sensor interface, Resistance-to-time converter, Resistance-to-pulse width converter.

1. Introduction

Various resistive sensors and transducers provide the result in changes of the resistance of sensing elements, whose resistance is changed as a function of the physical and chemical quantities being measured, for example, force, displacement, strain, flow, pressure, weight, temperature, light, humidity, moisture and gas concentration [1-8]. It is widely used in various sensor systems based on RTDs (Resistance Temperature Detectors), thermistors, light dependent resistors (LDR), strain gauges, various gas chemiresistive sensors, piezo-resistive sensors, soil moisture sensors, etc. Their values can be varied from a few tens Ω to several MΩ.

A resistive sensor interface must be used to quantify and display the resistive value of sensors and then convert them to a digital signal that can be processed by computer, DAQ system, microcontroller or microprocessor. The resistive sensor interfaces can be divided into two main types: 1) Direct resistive sensor interface with digital output; 2) Resistive sensor interface with intermediate conversion resistance-to-frequency, -period, -pulse width or -duty-cycle. The second type is called 'quasi-digital resistive sensor interface'.

The first type of interface includes single chip solutions (IC, ASIC, ASIP, FPGA), microcontroller based solution and Resistance-to-Digital Converters (RDCs) based on some mixed discrete components such as ADCs, filters, amplifiers, digital logical elements etc.

Let's consider some direct resistive sensor interfacing ICs, available on the modern market.

An easy-to-use resistance-to-digital converter optimized for platinum resistance temperature detectors (RTDs) - MAX31865, has introduced on the market by *Maxim Integrated Products, Inc.* [9]. An external resistor sets the sensitivity for the RTD being used and a precision delta-sigma ADC converts the ratio of the RTD resistance to the reference resistance into a digital form. The converter has the total accuracy ±0.5 ^{0}C (±0.05 % of Full Scale), 3.3 V supply and power-supply current 3.5 mA. The resistive range of MAX31865 is limited by P100 and P1000 resistive ranges.

The single chip solution PS081 for strain gauges is available from *ams* [10]. Its applications are limited by weight scales, force and torque measurements based on metal strain gages. The IC needs two external references: 4 MHz ceramic oscillator and 10 kHz RC oscillator.

The simple, single chip, direct resistive sensors interfacing circuit with high metrological performance and wide measuring range is described in [11]. It is based on the Universal Sensors and Transducers Interface (USTI) [12]. Despite of high metrological performance and wide functionality, its usage in WSN and IoT applications are limited due to relatively high current consumption (11 mA) and supply voltage (4.5 – 5 V).

As a response to modern applications challenges, the low-power, low-voltage modification of USTI integrated circuit – USTI-MOB has designed and introduced on the market [13]. Similar to the USTI, the UST-MOB also has a resistance-to-digital conversion mode.

This article is devoted to experimental investigation of USTI-MOB working in resistance measuring mode with aim to determine metrological performance in appropriate measuring mode. In addition to the direct resistive sensing interfacing, the USTI-MOB can convert all frequency-time output parameters of all existing resistive sensor interfaces with intermediate conversion to-frequency, -period, -pulse width or -duty-cycle.

2. Direct Resistive Sensor Interface

2.1 Interfacing Considerations

The USTI-MOB configuration for resistance measuring mode is similar to the USTI's appropriate mode with the following differences:

1) USTI-MOB needs 1.8 V supply voltage;
2) Quartz crystal oscillator's frequency must be 4 MHz;
3) The serial clock frequency for the I2C interface should be 20 kHz;
4) The serial clock frequency for the SPI interface should be 28 kHz;
5) The maximal possible baud rate for the RS232 interface is 1/76800 bps.

The considerations concerning the external components selection (C, R_0 and R_c) and programmable (selectable) charging time (T) are also the same as for the USTI [11, 12, 14].

2.2 Experimental Setup

The USTI-MOB was tested in the laboratory at the 25.0-29.2 ^{0}C temperature range and 20-57 % RH to check the metrological performance at resistive measurements. The IC together with all external components was assembled on the UCTI-MOB development board prototype.

The supply voltage of the development board was +14 V dc, provided by the programmable power supply FA-851 *Promax*. The digital storage oscilloscope OD-591 was used for the signal's shape monitoring on the USTI-MOB's SMPL pin (13) [12]. The experimental setup is shown in Fig. 1, and development board prototype – in Fig. 2.

The USTI-MOB was applied to the measurement of resistance in a wide range: from 20 Ω to 4 MΩ. Preliminary, 11 points were selected for the experiment from the mentioned range. Each resistors was measured 100 times (n=100), and appropriate statistic have been calculated. The nominals for external components R_c , C and charging time T value were calculated for each of point. The limiting resistor was constant R_0 = 424.51 Ω during all measurements.

In addition, the RDC was tested with various resistive sensing elements, for example, the RTD Pt100 and NTC.

R_x, R_0, R_c and C where measured with the precision LCR meter ST2819A [15], whose basic accuracy is better than ±0.05 %.

Fig. 1. Experimental setup to test the USTI-MOB in resistive measuring mode.

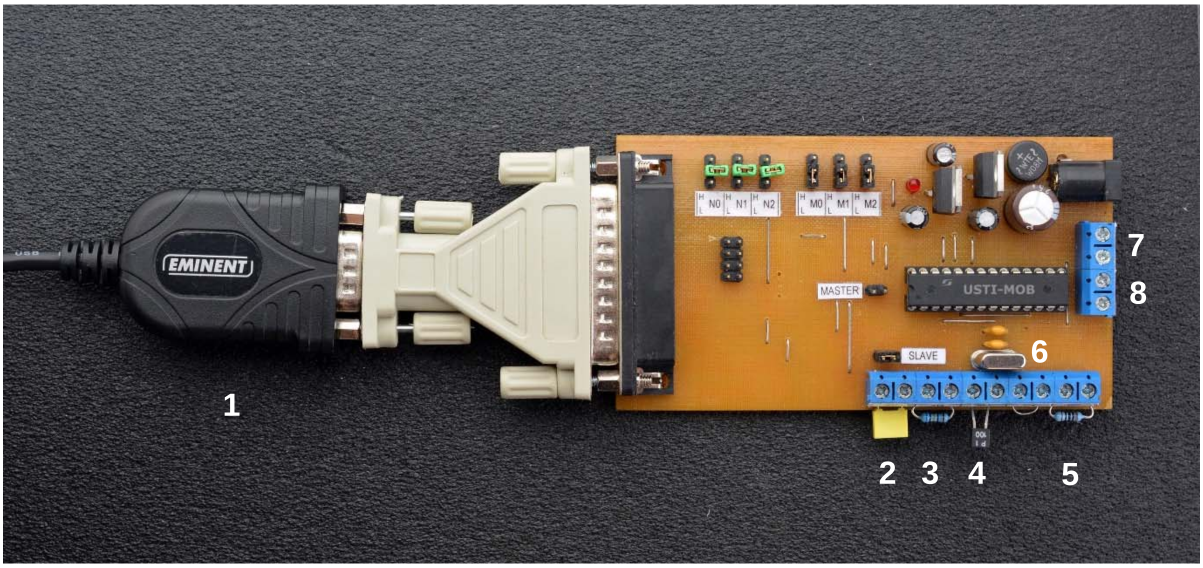


Fig. 2. USTI-MOB development board prototype: 1 - RS232-to-USB converter; 2 – calibration capacitor *C*; 3 – limiting resistor R_0; 4 – resistive sensing element, for example, Pt100 (R_x); 5 – reference resistor R_c ; 6 – quartz crystal oscillator, 4 MHz; 7, 8 – inputs for frequency-time parameters of signals.

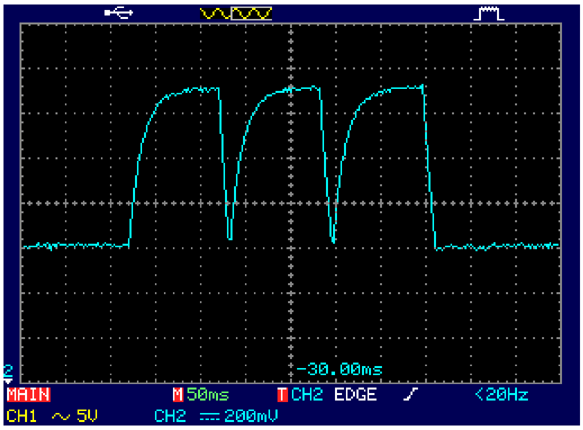
Preliminarily, the USTI-MOB was calibrated at the laboratory temperature range in order to eliminate an additional systematic error due to the quartz oscillator trimming inaccuracy (calibration tolerance) and a short term temperature instability [14, 16]. The USTI-MOB development board was connected to a PC working under the MS Windows 10 operation system, where terminal software Terminal v1.9b was running. The USTI-MOB was running in the slave communication mode with the RS232/USB interface.

2.3 Experimental Results

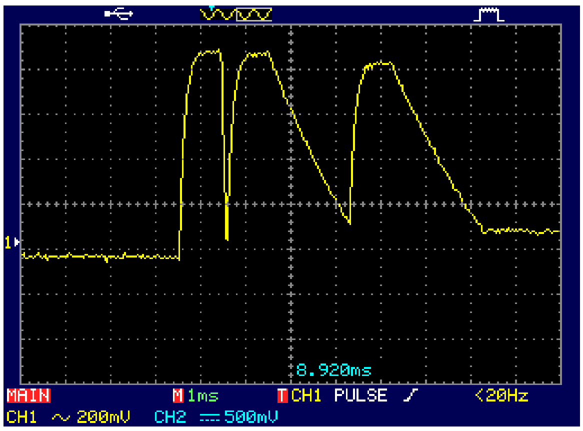
Oscillograms on the USTI-MOB's SMPL pin for the RTD Pt100, working for measurement 25-26 ^{0}C temperature are shown in Fig. 3 (a), and oscillograms for the NTC thermistor S861 (EPCOS) working in the same temperature range – in Fig. 3 (b).

The measurement results for various values of R_x are shown in Fig, 4 (a)-(k). The comparative performance summary of USTI and USTI-MOB ICs are adduced in Table 1.

The Statistical characteristics for all 11 points of measurements are adduced in Table 2. As it is visible from experimental results, the relative error is changed from ±1.54 to ±0.04 % dependent on the specified resistive range (20 Ω …4.5 MΩ). The best accuracy is achieved in the range from 1 kΩ to 50 kΩ. The accuracy can be improved by the usage more precision external components such as *C*, R_0 and R_c, for example, precision metal-dielectric resistors with ±0.1 % tolerance and better.



(a)



(b)

Fig. 3. Oscillograms on the USTI-MOB's SMPL pin (13) for RTD Pt100 (a), and NTC (b).

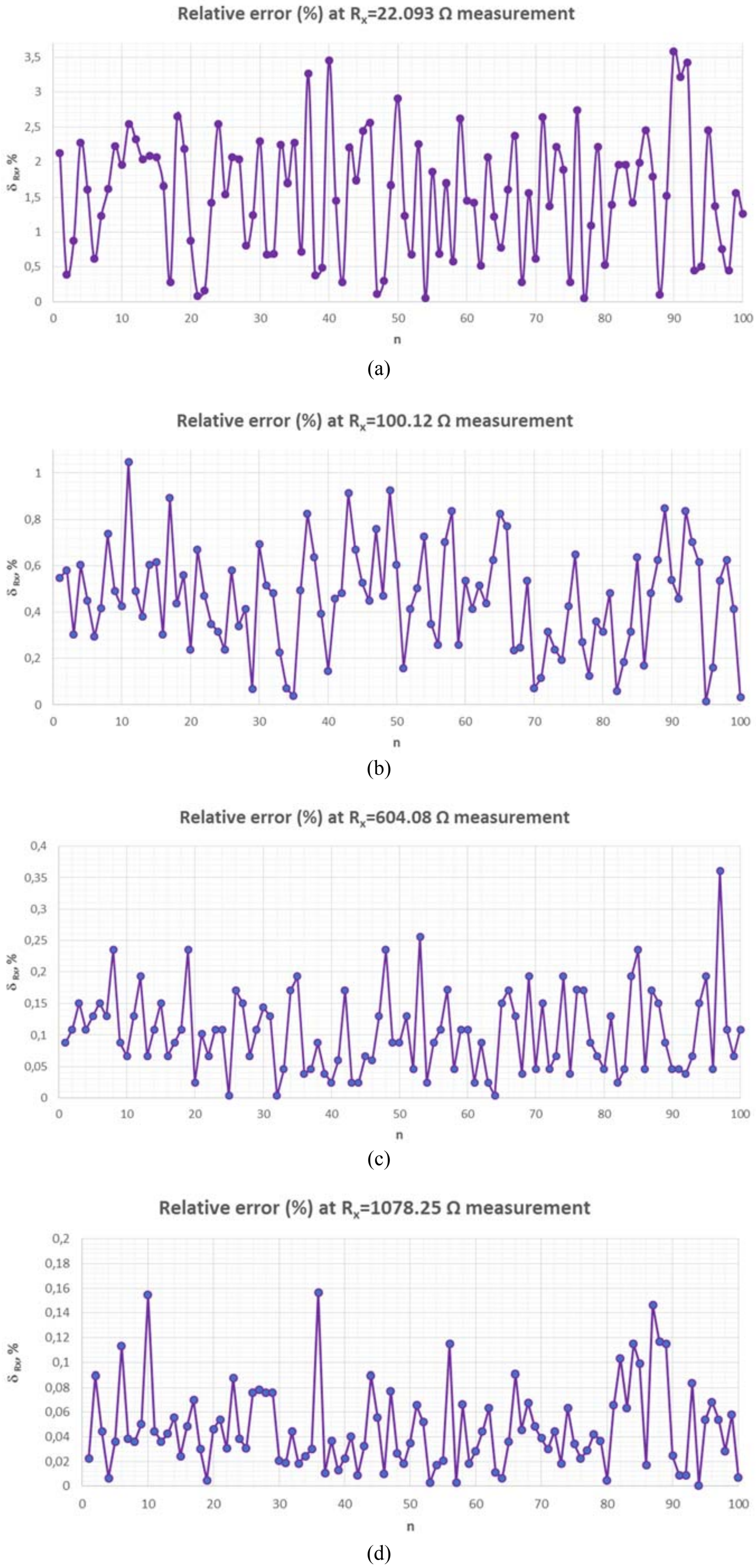
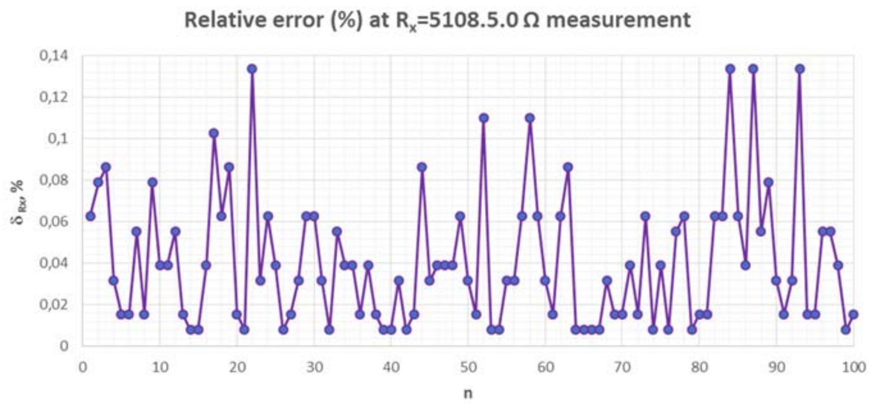
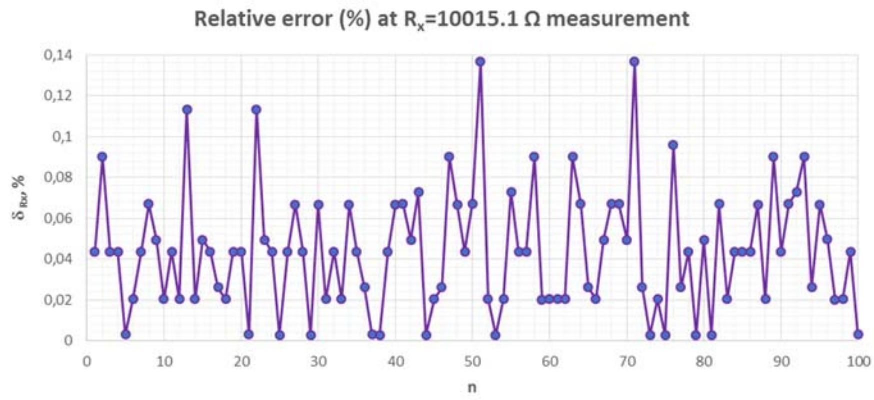


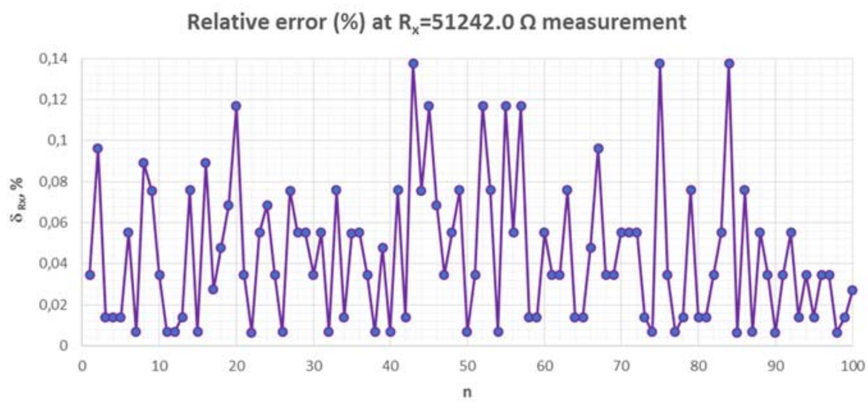
Fig. 4 (a-d). Relative errors for various R_x (n=100).



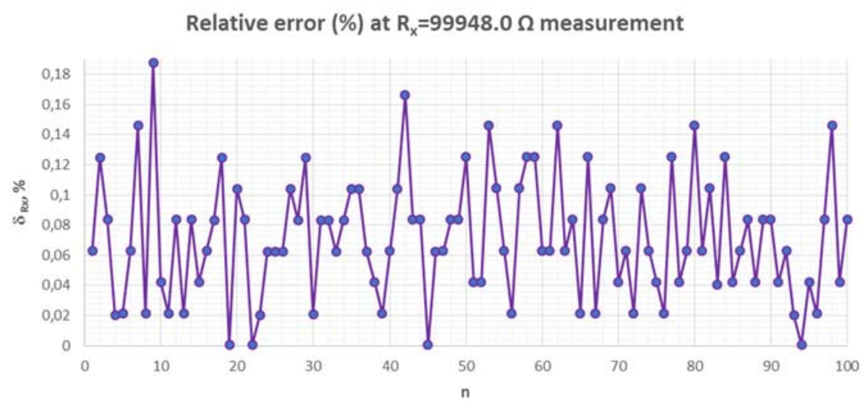
(e)



(f)

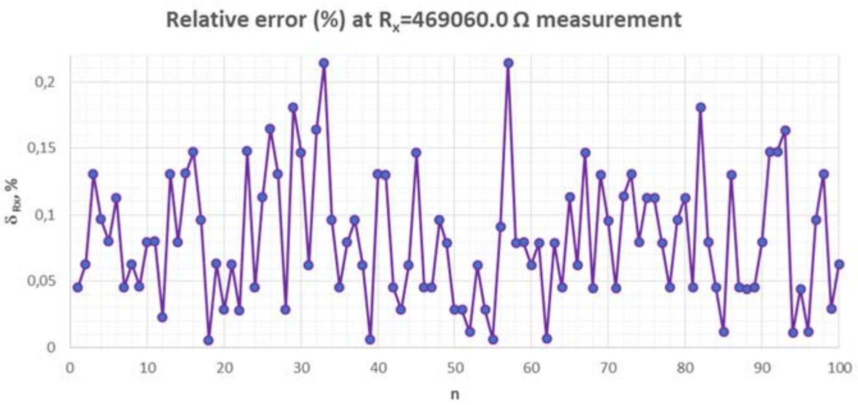


(g)

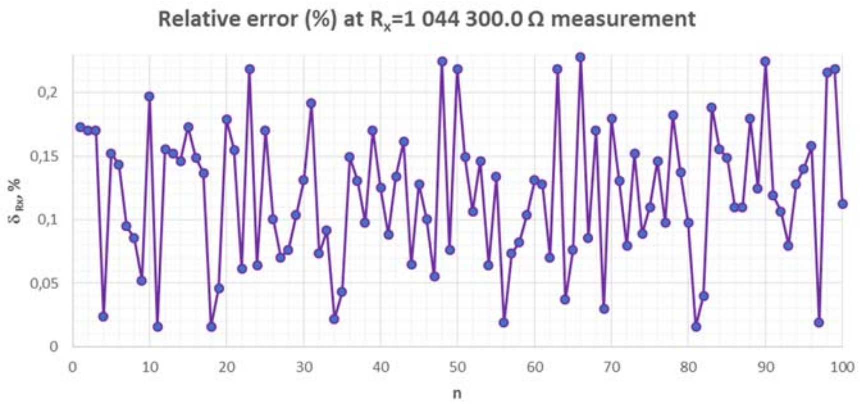


(h)

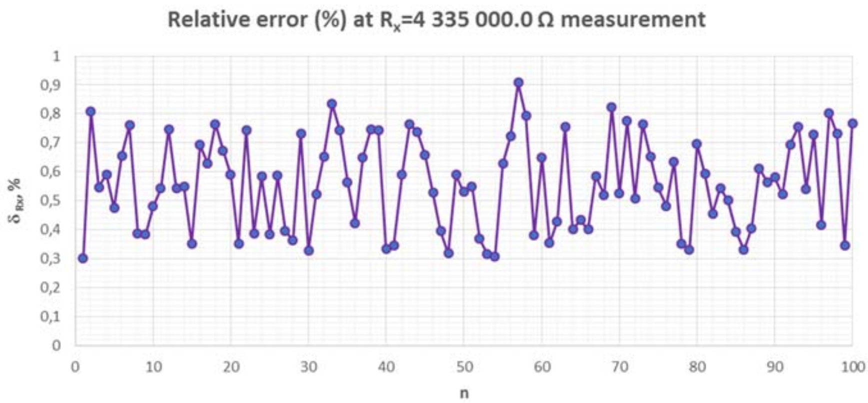
Fig. 4 (e-h). Relative errors for various R_x (n=100).



(i)



(j)



(k)

Fig. 4 (i-k). Relative errors for various R_x (n=100).

Table 1. Performance summary and comparison of USTI and USTI-MOB ICs.

Performance / IC	Input Range (Ω)	Measuring Accuracy (%)	Supply Voltage (V)	Supply Current (mA)
USTI	10 … 10 000 000	1.58 … 0.02	5.0	11
USTI-MOB	20 … 4 500 000	1.54 …0.04	1.2	0.85

Table 2. Statistical characteristics, Nominals of External Components, Charging Time and Calibration Constant.

	R_x (Ω)										
	22.093	**100.12**	**604.08**	**1078.25**	**5108.5**	**10 015.1**	**51 242.0**	**99 948.0**	**469 060.0**	**1 044 300.0**	**4 335 000.0**
Arithmetic Mean, Ω	21.7623	99.665	603.513	1078.39	5107.7	10012.6	51226.1	100017.5	468688.64	1043058.84	4310758.16
Minimum, $R_{x\ min}$, Ω	21,3017	99.071	601.901	1076.67	5101.68	10001.4	51171.6	99907.29	468053.92	1041919.17	4295653.00
Maximum, $R_{x\ max}$, Ω	22.2291	100.281	604.950	1079.94	5113.74	10024.7	51287.7	100135.37	469486.51	1044608.29	4321880.28
Sum of the Squared Deviations	4.3922	5.562	23.8052	37.950	645.797	2173.4	58754.97	190021.28	6132294.75	35910369.57	4615257061.0
Sampling Range ($R_{x\ max}$-$R_{x\ min}$), Ω	0.9274	1.210	3.049	3.273	12.061	23.292	116.06	228.08	1432.59	2689,12	26227.28
Variance	0.0443	0.056	0.2404	0.383	6.5231	21.954	593.49	1919.41	61942.37	362731.01	46618758.19
Standard Deviation	0.2106	0.237	0.4904	0.619	2.5541	4.686	24.3615	43.81	248.88	602.27	6827.79
Confidence Interval at P=0.95	0.1111	0.125	0.2587	0.327	1.3472	2.4715	12.8500	23.11	131.279	317.68	3601.49
Distribution Asymmetry	0.1356	0.030	0.00237	-0.1248	-0.2528	0.2200	0.0718	0.0503	-0.0848	0.2167	-0.0652
Excess	-0.5488	-0.186	0.88832	0.1807	-0.0210	-0.0014	0.3215	-0.0159	0.4027	-0.2954	-1.1373
Relative Error, %	1.54	0.458	0.105	0.047	0.041	0.0438	0.045	0.071	0.082	0.12	0.56
Minimal Relative Error, %	0.0553	0.014	0.003	0.0008	0.008	0.0027	0.0066	0.0004	0.0054	0.0159	0.3026
Maximal Relative Error, %	3.5814	1.047	0.361	0.157	0.134	0.1366	0.1374	0.1874	0.2145	0.2280	0.9077
Nominals of External Components and Charging Time											
Calibration Capacitor, C	94 µF	47 µF	3.9 µF	2.9 µF	412.95 nF	210.55 nF	46.5 nF	23 nF	6.1 nF	2.15 nF	503 pF
Reference Resistor, R_c (Ω)	22.079	99.46	603.55	952.60	5106.5	9989.9	51140.0	99783.0	464960.0	913700.00	4039000.0
Charging Time, T	100 ms	100 ms	9 ms	6.4 ms	900 µs	63 µs	100 µs	50.6 µs	13.4 µs	4.7 µs	1.1 µs

3. Quasi-Digital Resistive Sensor Interface

3.1 Overview

3.1.1 Resistance-to-Period Converters

In order to obtain large resistive variations, the use of oscillating circuit, performing a resistance to quasi-digital conversion is the best solution, because other type of interfaces (based on ADC) cannot guarantee a wide output range without the of either scaling factors or high-resolution pico-ammeters. In quasi-digital resistive sensor interfaces, the value of resistor is converted into frequency, period, duty-cycle or pulse width. Different values of these frequency-time parameters represent different resistor values.

A 16-bit readout circuit for gas sensor interface is described by Balaji Jayaraman and Navakanta Bhat in [17]. The front end signal conditioning circuit comprises a resistance – to – period converter with output from 0.1 μs to 1 μs (1 MHz to 10 MHz).The sensor resistance varies from 150 Ω to 85 MΩ.

A simple and linear, high resolution resistance-to-period converters for signal conditioning of resistive transducers are described in [18, 19]. In the first converter the resistance deviation R_x is converted into a proportional change in period T_x. The R_x was varied from 1000 to 3000 Ω, and period output varied from 15 ms to 75 ms. A resolution of 0.1% or better is obtainable from the converter over a wide resistance range. In the second converter, R_x was varied from 950 Ω to 2950 Ω, and the measured period output varied from a value close to 24.1 ms to a value ≈ 124.1 ms. The relative error was less than ±0.1 % in the entire range.

A simple resistance-to-period converter for resistive sensors is reported in [20]. The principle of converter utilizes the behavior of designed astable multivibrator, which is implemented using commercial available and low cost devices [20]. The resistance of converter is linearly dependent on period T_x and also can be converted to frequency with the invert proportional relationship $f_x=1/T_x$. The sensing resistance varied from 100 Ω to 1 kΩ, and period from ≈ 100 μs to 3250 μs. The relative worst-case error is 0.8 %.

Integrated CMOS resistance-to-period converter is described in [21]. The estimated resistance is from 0.1 MΩ to 10 GΩ, measured period – from 0.01 ms to 1000 ms. The relative error lower than 1 … 1.5 %.

3.1.2 Resistance-to-Frequency Converters

The simple and accurate resistance-to-frequency converters can be realized by using either crystals or ceramic resonators as stable, high performance frequency elements or oscillator ICs, for example, LTC1799, URFC-2501-250 [22, 23] and others. The LTC1799 has infinite frequency resolution, output square wave signal at any frequency from 5 kHz to 20 MHz. With a 0.1 % frequency-setting resistor, the frequency accuracy is typically better than ±0.5 %. The relation between R_x and frequency is simple:

$$fosc = \frac{10MHz \times 10k\Omega}{\mathrm{N} \times Rx} \tag{1}$$

where N is the on-chip divider setting of 1, 10 or 100. R_x can have any value from 3.32 kΩ to 1 MΩ.

The IC URFC-2501-250 is a resistance-to frequency converter, which provides frequency range from 1 MHz to 100 MHz (50 % duty-cycle) with one external resistor to set up the frequency.

A gas sensor conditioning circuit that allows a direct resistance-to-frequency conversion proportional to the concentration of ethanol vapor is reported in [24]. The input resistance is changed from 500 Ω to 30 kΩ, and output frequency – from 100 Hz to 6 kHz.

A resistance-to-frequency converter with generalized impedance converter for RTD Pt100 is reported in [25]. It has 2350 Hz – 3400 Hz output frequency range.

3.1.3 Resistance-to-Pulse width and –Duty-cycle Converters

A resistance deviation-to-pulse width converter for resistive sensors has proposed by Hoon Kim, et al [25]. The proposed circuit is applied to measure the temperature difference with the platinum resistance temperature detectors. The R_x resistor was varied in 0–100 Ω range, and pulse width – from 1.05 ms to 0.65 ms.

A signal conditioning circuit for push-pull-type resistive transducers is described in [26]. The resistive transducer becomes an integral part of a relaxation oscillator, the duty cycle ratio of the output of which becomes proportional to the measurand. Since the output depends only on the relative sensitivity of the transducer and a pair of dc excitation voltages, it is possible to obtain very low error: ±0.02 %. The value of R_x was varied from 0 to 12.221 kΩ.

A conditioning circuit for resistive sensors combining frequency and duty-cycle modulation of the same output signal is proposed by V. Ferrari et al [21]. It is based on a relaxation oscillator. Both the frequency and the duty-cycle of the output signal carry independent information coming from a pair of different sensors. Namely, the frequency of the output signal changes linearly with the resistance deviations detected by a Wheatstone bridge, while the duty-cycle is dependent on the resistance of a second sensor [27].

3.2. Experimental Setup and Results

In order to obtain a digital output from any quasi-digital converters, an appropriate frequency-, period-, duty-cycle- or pulse width-to-digital converter must be used. The USTI-MOB was especially designed to work with all mentioned frequency-time parameters of signals in appropriate ranges of measurements. To be neglected of USTI-MOB's conversion error, it must be in one order (or at least, in 5 times) less in comparison with error of quasi-digital converter [28].

Experimental set-up and results, which were obtained at measurements of frequency-time parameters of electrical signals were described in [13, 29, 30] by the author in details.

4. Conclusions

Experimental investigation of USTI-MOB IC working in the restive measuring mode has confirmed its high metrological performance, suitable for low power consumed applications such as sensor systems for IoT, wearable and mobile devices. This new IC can be used for both types of resistive sensor interfaces: direct resistive sensor interface with digital output, and quasi-digital resistive sensor interface.

In addition to sensor applications, the USTI-MOB can be used in digital multimeters for resistive measurements in a wide range, as well as for measurement of all frequency-time parameters of electrical signals and capacitance.

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